VULCAN: A compact neutron instrument for material stress characterization enabled by digital twin

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Abstract

Residual stresses in metallic and ceramic components significantly impact mechanical properties and lifetime, leading to excessive safety factors that increase material usage and costs. The automotive, energy, and aerospace sectors could potentially save over 18 billion Euros annually through improved understanding of stress in these components.
Current stress measurement techniques face significant limitations. Laboratory methods are accessible but often destructive, surface-limited, or restricted to single points or directions. While neutron- and synchrotron-based techniques overcome these limitations, their limited accessibility hinders widespread industrial adoption.
The VULCAN (Versatile ULtra-Compact Accelerator-based Neutron source) project addresses this gap by designing a compact, affordable neutron time-of-flight diffractometer optimized for industrial stress measurements. The instrument concept enables non-destructive mapping of stresses up to 10 cm deep in metals and ceramics, while measuring the full stress tensor.
Throughout the design phase, we developed a comprehensive digital twin of the VULCAN machine, combining neutron ray-tracing software McStas with high-energy Monte Carlo simulations of the target-moderator system. This digital approach enabled thorough optimization of the design parameters and machine performance.
The accuracy of our digital twin was recently validated through experimental testing at CERN's CLEAR facility, where measurements confirmed the predicted thermal neutron flux of the prototype target-moderator-reflector system.
Designed as a container-sized, turn-key solution, VULCAN will enable on-site installation at manufacturing companies or research infrastructures, improving accessibility to advanced stress measurements.